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(71) Applicant *(for all designated States except US)*: BOOKHAM TECHNOLOGY PLC [GB/GB]; 90 Milton Park, Abingdon, Oxon OX4 4RY (GB).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: SCHWABE, Nikolai, Franz [DE/GB]; Wolfson College, Oxford OX2 6UD (GB).

(74) Agent: UNWIN, Stephen, Geoffrey; Fry Heath & Spence, The Old College, 53 High Street, Horley, Surrey RH6 7BN (GB).

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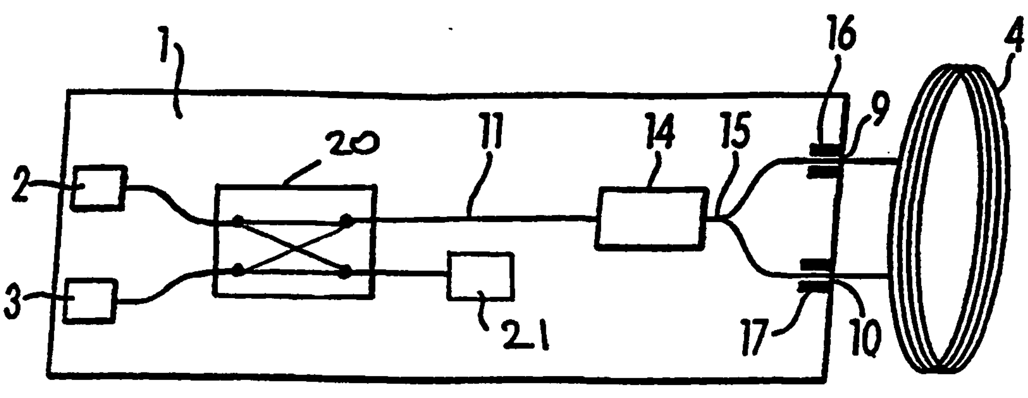
(54) Title: AN OPTICAL CIRCUIT



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(57) Abstract: An optical circuit integrated on a silicon-on-insulator chip, comprising a layer f silicon separated from a substrate by an insulating layer, for use in a fibre optic gyroscope which senses rotation rates by determining a phase shift due to the Sagnac Effect between light beams travelling around an optical fibre sensing loop (14) in opposite directions, the circuit comprising: first and second waveguides for transmitting light signals to and receiving light signals from the respective ends of the sensing loop (14); a coupler (15) for combining light signals received by the waveguides from the sensing loop (14); a phase modulators (16, 17) for determining a phase shift between light signals returning from the sensing loop (14); a light source (2); a light detector (3) and an optical switch (20) formed in the silicon layer arranged to be switched repeatedly to connect the light source (2) to the couple (15) when light signals are to be transmitted to the sensing loop (4) and to connect the coupler (15) to the light detector (3) when said light signals return from the sensing loop (4). The optical switch (20) may comprise a four-part Mach Zehnder interferometer.

AN OPTICAL CIRCUIT

TECHNICAL FIELD

This invention relates to an optical circuit for use in a fibre optic gyroscope.

BACKGROUND ART

Fibre optic gyroscopes for measuring rotation rates based on the Sagnac effect are known. When light traverses an optic fibre loop which is rotating about an axis perpendicular to its plane, the optical transit time of the light varies in dependence on the loop's rotation rate. For two optical signals traversing the loop in opposite directions, the Sagnac phase difference between them is proportional to the rotation rate.

Integrated optical circuits for use with such fibre optic gyroscopes have been proposed, for example, in US5194917 and in WO99/15856. The disclosure of WO99/15856 is hereby incorporated in this specification. The present invention aims to provide an optical circuit which reduces power losses which occur in such known circuits and which can be reliably and inexpensively manufactured.

DISCLOSURE OF INVENTION

According to a first aspect of the invention, there is provided an optical circuit formed on a silicon-on-insulator chip, comprising a layer of silicon separated from a substrate by an insulating layer, for use in a fibre optic gyroscope which senses rotation rates by determining a phase shift due to the Sagnac Effect between light beams travelling around an optical fibre sensing loop in opposite directions, the circuit comprising: first and second waveguides formed in the silicon layer for transmitting light signals to and receiving light signals from the respective ends of the sensing loop; a coupler formed in the silicon layer for combining light signals received by the waveguides from the sensing loop; phase determining means formed in the silicon layer for determining a phase shift between light signals returning from the sensing loop; a light source; a light detector and an optical switch formed in the silicon layer arranged to be

switched repeatedly to connect the light source to the coupler when light signals are to be transmitted to the sensing loop and to connect the coupler to the light detector when said light signals return from the sensing loop.

According to another aspect of the invention there is provided a fibre optic gyroscope comprising such an optical circuit.

Other preferred and optional features of the invention will be apparent from the following description and the subsidiary claims of the specification.

BRIEF DESCRIPTION OF DRAWINGS

The invention will now be further described, merely by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a first embodiment of a known fibre optic gyroscope as described in WO99/15856;

Figure 2 is a schematic diagram of a second embodiment of a known fibre optic gyroscope as described in WO99/15856;

Figure 3 is a schematic diagram of a further known form of fibre optic gyroscope similar to those described in WO99/15856;

Figure 4 is a schematic diagram of an embodiment of the present invention; and

Figure 5 is a diagram of a preferred form of optical switch for use in the gyroscope of Figure 4.

BEST MODE OF CARRYING OUT THE INVENTION

The fibre optic gyroscope illustrated in Figure 1 comprises an integrated optical circuit, fabricated on a silicon-on-insulator chip 1. This comprises an upper

layer of silicon separated from an underlying layer of silicon, by an insulating layer, such as silicon dioxide. Such a substrate preferably comprises an upper layer of silicon 3 to 15 microns thick separated from the underlying silicon layer by a layer of silicon dioxide at least 0.1 microns thick and preferably at least 0.3 microns thick. Such substrates are readily commercially available. References in the following description to the silicon layer refer to the upper layer described above.

The integrated optical circuit 1 connects together a light source 2, a light detector 3, and an optical fibre loop 4, which forms the sensing element of the gyroscope.

The integrated optical circuit 1 comprises first and second fibre connectors 5 and 6 for receiving optical fibres 7 and 8 transmitting light to and from the light detector 3 and the source 2. The fibre connectors 5 and 6 comprise grooves, typically V-grooves, formed in the silicon layer.

Further fibre connectors 9 and 10 are provided for receiving the ends of the fibre optic loop 4. Rib waveguides 11 are formed in the silicon layer of the chip to optically connect the fibre connectors 5, 6, 9 and 10, the rib waveguides from the connectors 5 and 6 joining at a first Y-junction 12, and passing through a spatial filter 13 and a polariser 14 before dividing at a second Y-junction 15. The waveguides extending from the second Y-junction 15 pass through phase modulators 16 and 17 and then to the connectors 9 and 10. The Y-junction 15 thus serves to direct light in both directions around the sensing coil 4 and to re-combine the counter propagating light received back on the chip 1. The waveguides 11 may be tapered at the waveguide-optical fibre connections to provide mode matching and good optical power coupling. Details of a suitable form of taper are provided in GB-A-2317023.

Th rib waveguides 11, the fibre connectors 5, 6, 9 and 10, and the phase modulators 16 and 17 are all constructed in the same silicon layer. This greatly

simplifies fabrication of the circuit, enables further components such as light sources, light detectors and fibres to be passively align d with the rib waveguides 11 and avoids potential problems associated with the change of material, and hence the refractive index, at the interfaces between the waveguides and other monolithically integrated components.

The use of a silicon-on-insulator substrate enables the fibre connectors to be fabricated in accordance with the applicants' co-pending application WO97/42534 in which the rib waveguide is constructed to overhang the end of the V-groove to facilitate butt coupling of the waveguide with an optical fibre positioned within the V-groove.

The rib waveguides 11 and fibre connectors 5, 6, 9 and 10 are also self-aligned to the crystallographic planes of the silicon layer and their relative positions can be determined by a single photolithographic step during fabrication of the circuit.

The phase modulators used in the present invention for signal interrogation may comprise a p-i-n diode formed across a rib waveguide such as, for example, disclosed in WO95/08787, in which doped regions are provided on either side or alongside the silicon rib waveguide. An electrical signal applied across the diode causes free charge carriers to be injected into the rib waveguide and so alter its effective refractive index. There is no material mis-match between the waveguides 11 and such modulators so coupling losses therebetween are avoided. Such p-i-n modulators are capable of modulation up to many MHz which is more than adequate for gyroscope demodulation schemes for both open and closed loop systems.

A phase modulator is preferably provided in each of the waveguides leading to the respective ends of the optical fibre sensing loop although in some arrangements only a single phase modulator is required.

The polariser 14 is preferably integrated on the chip 1 and may also be based on a silicon rib wav guide structure, e.g. by modifying the dielectric cladding (e.g. usually silicon dioxide) and replacing part of it with a buffer layer of high refractive index and a metal coating such as aluminium. A suitable form of polariser is disclosed in WO99/12062. However, other forms of polarising means may be used to polarise the light transmitted to the sensing loop.

The spatial filter 13 is provided to help reduce the effect of stray light in the substrate associated with the Y-junction 12, which could couple into the waveguide. The degree of spatial filtering required will depend on the amount of stray light (e.g. produced by scattering at interfaces, by Y-junctions and, to a lesser extent, by couplers) and will depend on the requirements of the application.

The spatial filter may be in the form of a curved section of a rib waveguide (as shown in Figs. 1 and 2) or may be formed by a sharp 90 degree bend or may be provided by other means, e.g. the provision of one or more mirrors. The spatial filter is preferably also integrated on the chip.

Figure 2 shows an arrangement similar to that of Figure 1 except that the light source and light detector 2 and 3 are provided on the silicon-on-insulator chip rather than being mounted off-chip.

The light source 2 typically comprises a laser diode integrated on the chip 1. The light source 2 may be passively aligned with the waveguide leading thereto by mounting it in a location recess formed in the silicon layer. The positions of the location recess and of the waveguide can be determined by a single lithographic step during fabrication of the chip so they are automatically aligned with each other. Location of the laser diode in the direction perpendicular to the face of the chip may also be determined by the position of an interface of the insulating layer in the silicon-on-insulator chip which provides a natural etch stop. Further details of the alignment of a laser diode with a rib waveguide are

giv n in US5881190. Superluminescent diodes (SLDs) and edge light emitting diodes (ELEDs) may also be us d as the light source 2.

The light detector 3 typically comprises a photodiode. This may be integrated on the chip and located thereon in a similar manner to the laser diode as described above. Alternatively, it may be mounted over a recess in the silicon layer and an angled facet provided in the recess to re-direct light from the waveguide to the photodiode. Alignment between the facet and the waveguide can, again, be achieved automatically as they are formed in the same silicon layer and their positions determined by a single lithographic step. Further details of this are given in WO98/35253.

These alignment techniques help reduce coupling losses and simplify the manufacturing process so making it quicker and less expensive.

Directional couplers may be used in the circuits described above in place of the Y-junctions. Figure 3 shows the use of a 2 x 2 coupler 18 in place of the Y-junction 12 in an arrangement similar to that of Figure 2. Such couplers comprise rib waveguides which are positioned close to each other so that a light wave travelling in one waveguide overlaps with the other waveguides and is thus coupled therewith. The loop shown in the Figures represents the coupling region. Figure 3 also showns a monitor photodiode 19 connected to an output of the coupler 18.

Other types of Y-junction or couplers may also be used (with spatial filters when necessary).

A problem associated with Y-junctions or couplers of the type described above is that the light input on one port is split between the other ports in a proportion depending upon th design of the d vice. Thus, the output port leading to the sensing coil 4 only receives a proportion of the light input to the Y-junction or coupler. This loss occurs both wh n th light is passing through the Y-junction

or coupler from the light source to the sensing coil and when light is passing through the Y-junction or coupler from the sensing coil to the light d tector. In practice, 3dB may be lost in each direction, giving an overall loss of 6dB. In some circumstances, this power loss can be a serious disadvantage, particularly in high temperature applications (80°-85°C) when the power output of the light source may be much reduced.

This invention aims to reduce such power losses by replacing the Y-junction of the coupler with an optical switch, e.g. a cross bar switch 20 such as that shown in Figure 4. In a first state of the switch 20, the light source 2 is connected to the waveguide 11 and the light detector 3 is connected to a light monitor 21 or beam dump (a photodiode acts as a beam dump as well as a light detector). In a second state of the switch 20, the waveguide 11 is connected to the light detector 3 and the light source 2 is connected to the light monitor 21.

The optical switch 20 can thus be arranged to connect the light source 2 to the waveguide 11 to transmit light signals to the sensing coil 4 and then be switched so the light signals returning from the sensing coil are directed back to the light detector 3. The switching speed thus needs to be fast enough to enable switching from one state to the other within the time taken for the light signals to be transmitted around the sensing loop 4.

The optical switch 20 may comprise a four port Mach-Zehnder interferometer as shown in Figure 5. This preferably comprises phase modulators, e.g. p-i-n diodes similar to the pin diodes 16, 17 referred to above.

One or more p-i-n diode phase modulators may be used in a variety of configurations to provide an optical switch and Figure 5 illustrates a four-port Mach-Zehnder interferometer comprising two pathways extending between two four port evan scent couplers 22 and 23 (represented in the Figure by loops between wav guides positioned in close proximity to each other) with a first p-i-n diode phase modulator 24 in one pathway and a second p-i-n diod phase

modulator 25 in the other pathway. The functioning of such an interferometer is well known. By appropriate control of the phase modulator 24 and/or 25, the effective ptical lengths of th two pathways can be controlled such that the Mach-Zehnder interferometer operates as a cross-bar switch, used here effiectively as a 1 x 2 switch, connecting the waveguide 11 either with the light source 2 or with the light receiver 3. It should be noted that only one of the phase modulators 24 or 25 need be used to operate the switch although both are preferably provided to allow either for more sophisticated control of the Mach-Zehnder interferometer or to provide a back up should one of the modulators fail.

Any other integrated 1 x 2 optical switch may also be used.

Such an optical switch may also be used in place of the Y-junction or coupler leading to the light source and light detector in the arrangements shown in Figures 1 and 2 and the other arrangements disclosed in WO99/15856

The optical switch thus avoids power losses by, in one state, directing all the power from the light source 2 to the sensing coil and, in the other state, directing all the power returning from the sensing coil to the light detector 3.

The optical switch should have a bandwidth at least as great as that of the modulators 16 and 17. This can be easily achieved using the same type of pin-diode for each of the modulators 16,17, 24 and 25.

The optical circuit may be operated with a light source 2 providing a continuous output signal. This has the advantage of providing a stable output without wavelength fluctuations which can arise if the power output is switched on and off. The average power reaching the detector will be similar to that of a conventional circuit but the peak power receiv d will be increas d so l ading to an increase in sensitivity.

In an alternative arrangement, the light source 34 may provide a pulsed output. In this case, operation of th optical switch is synchronised with that of the light source so that each pulse is transmitted to the sensing coil and the return signal from the sensing loop 4 is directed to the light detector 3 in the time intervals between the output pulses of the light source. This has the advantage of reducing the overall power consumption of the light source. This also results in less heat dissipation by the lights source.

It should be noted that the position of the polarisers 14 may be varied so long as a polariser is provided between the light source and each sensing coil 4 and between each sensing coil 4 and each detector 3. The order of the polariser 14 and spatial filter 13 is also immaterial.

It will be appreciated that the use of a silicon-on-insulator substrate allows all the components of the gyroscope (except for the light source and light detector and the sensing loop) to be monolithically integrated in the silicon layer so reducing the number of interfaces in the circuit. Thus, optical power coupling losses due to refractive index steps with changes in waveguide material are avoided or eliminated. The light source and light detector may be hybridised on the chip and the nature of the silicon-on-insulator substrate also allows for the self-alignment of optical sources and detectors and for self-alignment of optical fibres to the rib waveguides as described above.

The use of silicon waveguides incorporated in a silicon-on-insulator substrate allow the integrated circuit to be made very compact. A fibre optic gyroscope having an integrated optical circuit on a silicon-on-insulator substrate may typically be from 3 mm x 20 mm for a single coil arrangement. This improves the cost-effectiveness of production as well as reducing the size of the device.

CLAIMS

1. An optical circuit formed on a silicon-on-insulator chip, comprising a layer of silicon separated from a substrate by an insulating layer, for use in a fibre optic gyroscope which senses rotation rates by determining a phase shift due to the Sagnac Effect between light beams travelling around an optical fibre sensing loop in opposite directions, the circuit comprising: first and second waveguides formed in the silicon layer for transmitting light signals to and receiving light signals from the respective ends of the sensing loop; a coupler formed in the silicon layer for combining light signals received by the waveguides from the sensing loop; phase determining means formed in the silicon layer for determining a phase shift between light signals returning from the sensing loop; a light source; a light detector and an optical switch formed in the silicon layer arranged to be switched repeatedly to connect the light source to the coupler when light signals are to be transmitted to the sensing loop and to connect the coupler to the light detector when said light signals return from the sensing loop.

2. An optical circuit as claimed in claim 1 having fibre connectors for connecting the waveguides to the respective ends of the fibre optic sensing loop.

3. An optical circuit as claimed in claim 2 in which the phase determining means comprises at least one phase modulator provided in the first or second waveguide.

4. An optical circuit as claimed in claim 3 in which a first phase modulator is provided in the first waveguide and a second phase modulator is provided in the second waveguide.

5. An optical circuit as claimed in any of claims 2 to 4 in which the optical switch comprises a four-port Mach-Zehnder interferometer with a first port connected to the light source, a second port connected to the light detector and a third port connected to the coupler.

6. An optical circuit as claimed in claim 5 in which the Mach-Zehnder interferometer comprises phase modulators.

7. An optical circuit as claimed in claim 3, 4 or 5 in which the phase modulator(s) forming the phase determining means comprises pin diodes.

8. An optical circuit as claimed in claim 6 in which the phase modulators of the interferometer comprise pin diodes.

9. An optical circuit as claimed in claim 5 in which a fourth port of the interferometer is connected to a light monitor or a beam dump.

10. An optical circuit as claimed in any preceding claim in which the light source is arranged to provide a continuous output.

11. An optical circuit as claimed in any of claims 1 to 9 in which the light source is arranged to provide a pulsed output, the optical switch being arranged to synchronise with the pulses so as to direct the pulses to the coupler.

12. An optical circuit as claimed in any preceding claim having polarising means for polarising the light signals transmitted to the sensing loop.

13. An optical circuit substantially as hereinbefore described with reference to the accompanying drawings.

14. A fibre optic gyroscope comprising an optical circuit as claimed in any of claims 1 –13.

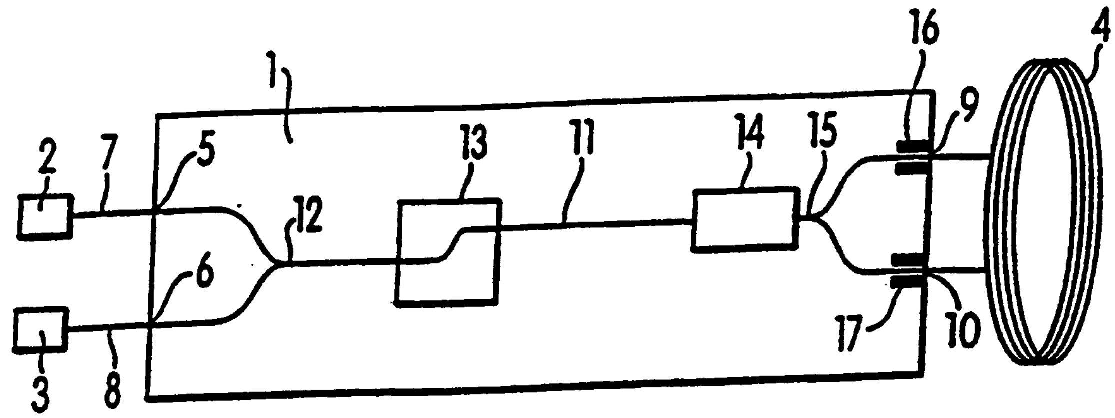

Fig.1

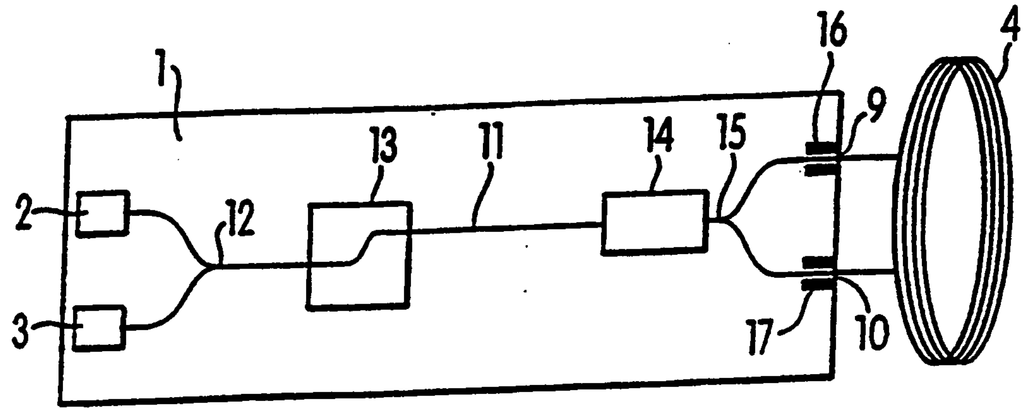

Fig.2

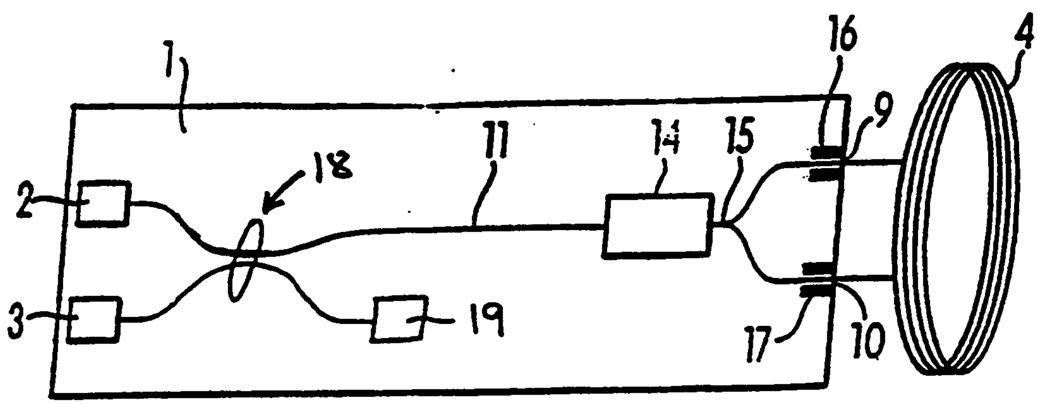

Fig.3

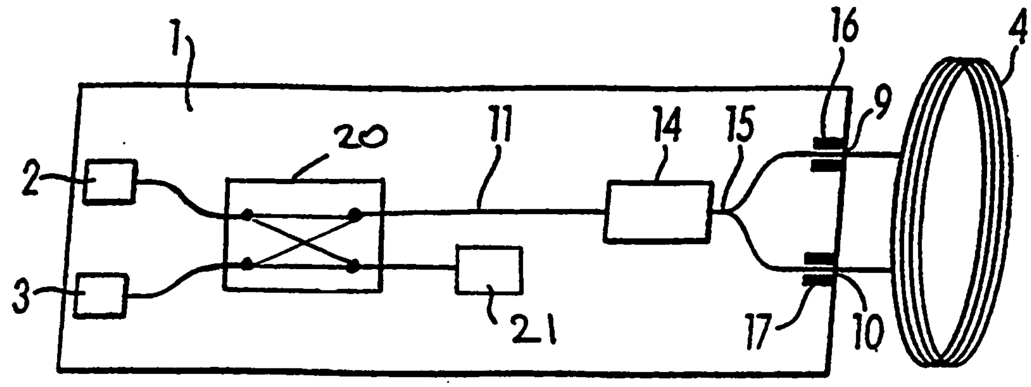

FIG. 4

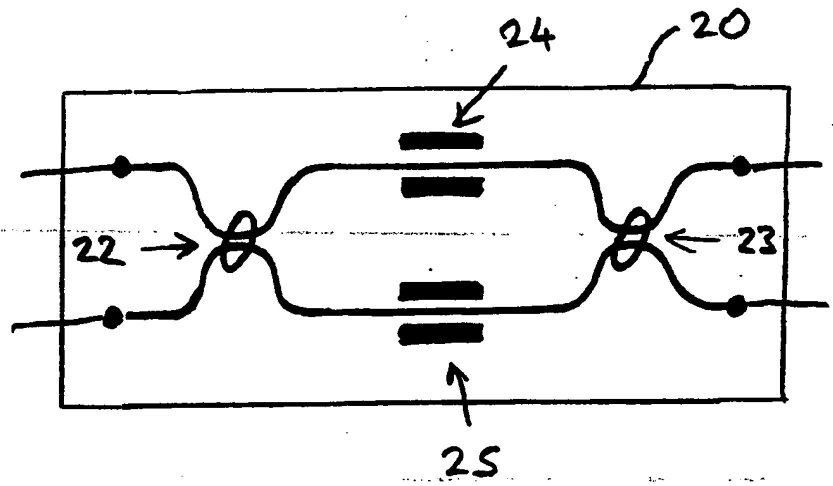

FIG. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/02659

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01C19/72

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 566 757 A (SMITHS IND AEROSPACE & DEFENSE) 27 October 1993 (1993-10-27) abstract page 23, line 20 - line 39 page 32, line 33 - line 40	1-4,10, 12,14
Y	WO 99 15856 A (BOOKHAM TECHNOLOGY LTD) 1 April 1999 (1999-04-01) cited in the application abstract; figures 2,6	1-4,10, 12,14
A		8
A	PATENT ABSTRACTS OF JAPAN vol. 018, no. 333 (P-1759), 23 June 1994 (1994-06-23) & JP 06 082257 A (JAPAN AVIATION ELECTRON IND LTD), 22 March 1994 (1994-03-22) abstract	1

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
17 October 2000	24/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hunt, J

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/02659

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 920 666 A (SADOWSKI ROBERT W ET AL) 6 July 1999 (1999-07-06) abstract -----	5-7

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
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